

New multi-channel electron energy analyzer with cylindrically symmetrical electrostatic field

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Abstract. This paper discusses an electron energy analyzer with a cylindrically symmetrical electrostatic field, designed for rapid Auger analysis. The device was designed and built. The best parameters of the analyzer were estimated and then experimentally verified.

INTRODUCTION

One of the nearly nondestructive methods to examine surfaces of materials is the analysis of Auger electrons. These have energies from the range roughly from 50 to 2000 eV and are emitted from the top few nanometers giving unique valuable surface sensitivity. Most common sequential analyzers, such as CMA or CHA, are used. Although many tens of percents of emitted electrons can be collected by some analyzers, this still may not be sufficient for fast analysis, because energies are analyzed sequentially. Each time the particular detection energy is changed, there is a dead time needed by the system to get into the desired state. Such analyzers then need much more time to obtain a spectrum. This can be a serious issue for time dependent experiments, if the sample can be easily damaged by the electron beam, or if a spectrum is acquired for each pixel in an entire image.

In general, in order to reduce the time needed to acquire a spectrum, either the solid angle intercepted by the analyzer can be increased, or parallel detection can be employed. It was shown in [1] that it is possible to acquire the entire energy spectrum of interest simultaneously. The basis of the analyzer used was the two dimensional hyperbolic field [2][7].

The approach in this work is the development of an analyzer that keeps all the advantages of parallel acquisition and that also has a possibility to increase the solid angle by adding cylindrical symmetry with a new focusing property. The advantage of this solution is a further decrease of the time needed to acquire the spectrum.

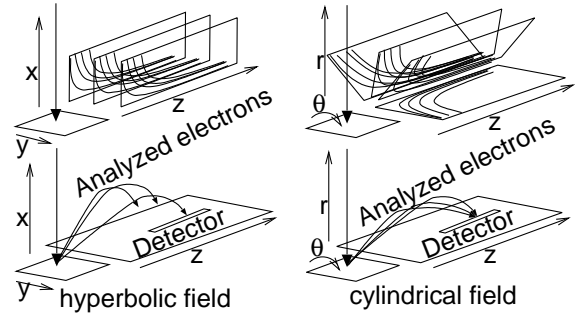


FIGURE 1. The hyperbolic field (left-hand side) and the cylindrically symmetrical field (right-hand side). The trajectories in the cylindrically symmetrical field are focused onto the detector, increasing the detected signal. Another focusing property is added.

CYLINDRICALLY SYMMETRICAL ELECTROSTATIC FIELD

There are several conditions for the electrostatic field to be usable for electron energy analysis. First, Laplace's equation has to be satisfied. The trajectories of the electrons analyzed by the field have to be focused in the detector plane. In this case, because the field has cylindrical symmetry, there must be the axis to axis focusing property of the field [3]. This means that the electrons starting from one point on the axis are focused back to the axis of symmetry, on which the detector is situated. The electrostatic field satisfying all above conditions may be defined by the potential:

$$\varphi = V_0 z \log(r/R_0), \quad (1)$$

where V_0 is a constant characterizing the strength of the field, R_0 is the internal radius, below which there is no field, r and z are cylindrical coordinates. Knowing the potential, the equations of motion in the cylindrical coordinate system can be written:

$$\begin{aligned} m(\ddot{r} - r\dot{\theta}^2) &= -qV_0 z/r \\ m(r\ddot{\theta} + 2\dot{r}\dot{\theta}) &= 0 \\ m\ddot{z} &= -qV_0 \log(r/R_0). \end{aligned} \quad (2)$$

When the axis to axis focusing mode is employed, it can be supposed that the particles are starting from the axis, and thus the angular component of the velocity is zero. Then the equations of motion can be simplified to:

$$\begin{aligned} m\ddot{r} &= -qV_0 z R_0 / r \\ \ddot{\theta} &= 0 \\ m\ddot{z} &= -qV_0 \log(r/R_0). \end{aligned} \quad (3)$$

In contrast to the hyperbolic field case [2], this set of differential equations does not have an analytical solution; it has to be integrated numerically. The trajectories were calculated using the Runge-Kutta integration method [6].

It is also necessary to find the parameters of the field that produce the best focusing and thus also the best resolution for a specified solid angle of acceptance. One possible solution of this problem is using a minimization algorithm. In this case for various energies several trajectories were modeled. The sum of squares of deviations of the endpoint positions is a satisfactory function to minimize.

From the trajectories of electrons in the field it is possible to calculate the dispersion and the best reachable resolution of the analyzer employing this kind of electrostatic field.

The dispersion can be calculated just from the central trajectory for each energy. Instead of the traditional definition of the dispersion,

$$D_r(E) = E \partial z / \partial E,$$

where the dispersion is relative to the energy, the absolute dispersion,

$$D_a(E) = \partial z / \partial E,$$

is more suitable. For the CMA or other analyzers, where the detected energy is tuned, the relative definition is more applicable, because then the dispersion is nearly independent of energy. For the parallel analyzer the absolute definition is more suitable for the same reason.

A similar problem is the definition of the resolution. In case of the CMA the relative definition is used.

$$R_r(E) = \frac{E}{\Delta E(E)}$$

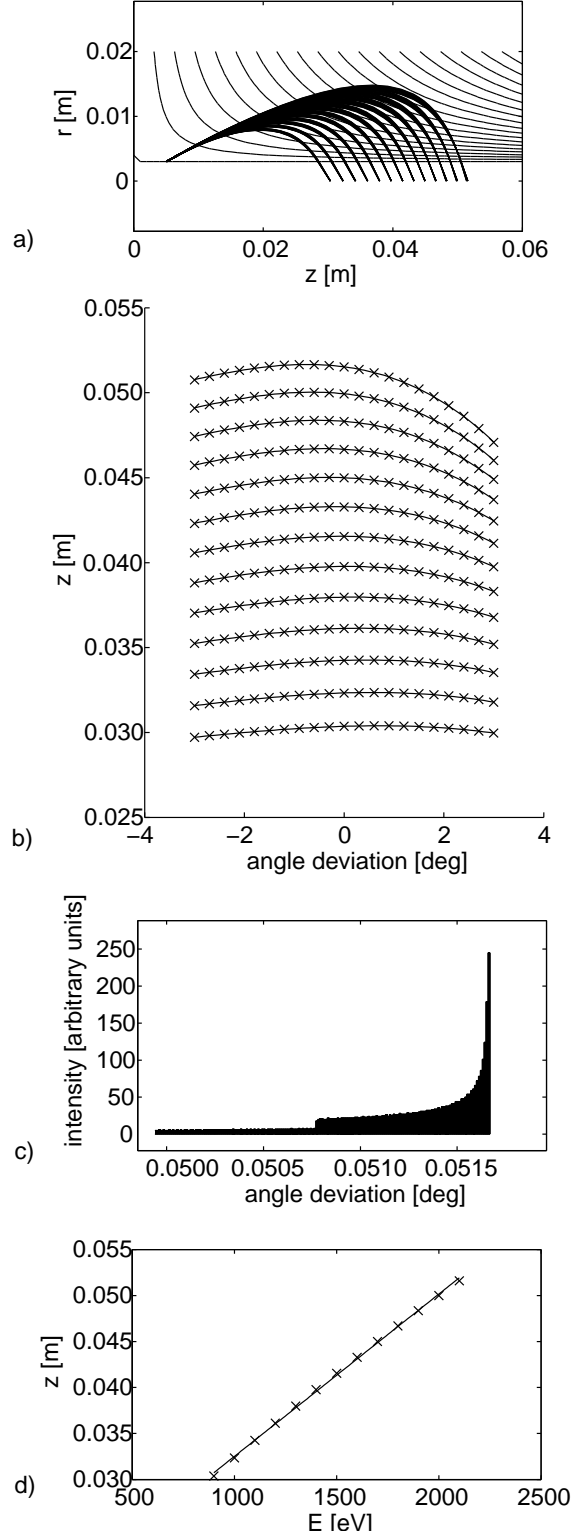


FIGURE 2. The cylindrically symmetrical field. a) Equipotentials and trajectories of electrons in the field for energies in the range of 900—2100 eV. The energy step is 100 eV. Trajectories start at [0,0]m, b) Dependence of the z-coordinate of the trajectory endpoint on the entry angle. (The presence of a maximum indicates first order focusing), c) The point spread function (PSF) for the energy of 2100 eV d) Dependence of the z-coordinate of the endpoints on energy (integral of the dispersion)

The reason is again the fact that this value is almost constant. For the same reason, in the case of the cylindrically symmetrical field analyzer or hyperbolic field analyzer (HFA) the absolute definition is more suitable.

$$R_a(E) = \Delta E(E)$$

To be able to calculate the best possible resolution (the resolution affected only by the properties of the electrostatic field) for each energy a set of calculated endpoints of electron trajectories is needed. Because the analytical expressions of the trajectories are not known, whole trajectories have to be calculated instead of the endpoints only. The calculation then takes more time than in case of the HFA.

Calculation of the trajectories and their endpoints showed that for different angles of entry different endpoints are obtained as expected. When the entry angle is increased, the endpoint is getting farther, until a turning-point is reached. Then the detected coordinate is decreasing. See Fig. 2b. In fact, the existence of this turning-point enables focusing (first order focusing in this case). The dependence of the endpoint coordinate on the angle of entry can be very well approximated by a cubic polynomial for all energies. The coefficients of such polynomials are then dependent on energy and can be also very well approximated by quadratic polynomials. The detected coordinate of the endpoint can then be expressed as

$$z(E, \psi) = \sum_{i=0}^2 \sum_{j=0}^3 k_{ij} E^i \psi^j. \quad (4)$$

The coefficients k_{ij} can be calculated, and then from (4) any number of endpoints can be interpolated. Then it is possible to calculate resolution from the histogram of positions, (Fig. 2c) and dependence of the endpoint position on electron energy, which is in fact the integral of the dispersion. See Fig. 2d. For the resolution, the Δz is defined. In this case, the density of endpoint positions (PSF in this case) is divergent, because of the existence of turning-points. Δz must be defined as the distance between 20%—80% of the distribution function. The Δz varies with energy. The calculation showed that the absolute dispersion D_a is very close to a constant. See Fig. 2d. Thus

$$\Delta E = \Delta z / D_a.$$

The modeling of the trajectories in the analytical field showed that the best focus is obtained when the energies of the analyzed electrons are between 1000 eV and 2000 eV instead of the desired range of 50 eV—1000 eV, considering that the position of the detector is given. It is possible to use this higher range of energies by placing an accelerator in front of the analyzer entrance.

SIMULATIONS

To create a real analyzer with a field that has the same analytical properties as the field defined by Eq. 1,

electrodes of a particular shape have to be used. The outer shape of the analytical area of the analyzer is determined by the geometry of the chamber, electron column and detectors. The electrodes must be placed where the equipotentials cross the outer shape of the analyzer. These electrode shapes are then analytically calculated, and the shape functions are obtained. In some cases the problem leads to transcendental equations, and numerical methods must then be used.

To examine the behavior of the analyzed electrons in the real analyzer, which is created by charged electrodes, simulation software can be used. The CPO [5] software was suitable for this 3D pure electrostatic problem. This software uses the boundary integral method to calculate the value of the electrostatic potential at any particular point in the analyzer. It can also be used to calculate the trajectories of analyzed electrons. The boundary integral method is based on calculations of charge distributions on electrodes. Therefore the electrode shapes had to be divided into a set of smaller triangular or rectangular segments. When the charge distribution is known, electron motion within the field can be simulated and for each electron a trajectory endpoint can be obtained. For the endpoints obtained from CPO-3D simulation Eq. (4) is also valid and the coefficients may be calculated. Out of them it is possible to figure out the resolution and the dispersion.

THE DEVICE

Fig. 4a shows a photograph of the device. The analyzer must satisfy several conditions to be usable in an ultra-high-vacuum electron microscope system:

- The analyzer must fit into the chamber and not collide with other parts of the microscope.
- Only ultra-high-vacuum compatible materials must be used.
- All parts of the analyzer have to be bakeable. They must stable at higher temperatures.
- Magnetic materials must be avoided.

The conditions above strongly limit the usable materials. The device had to be designed with respect to the system used. In this case the experiment took place in the electron microscopy laboratory at the Department of Physics

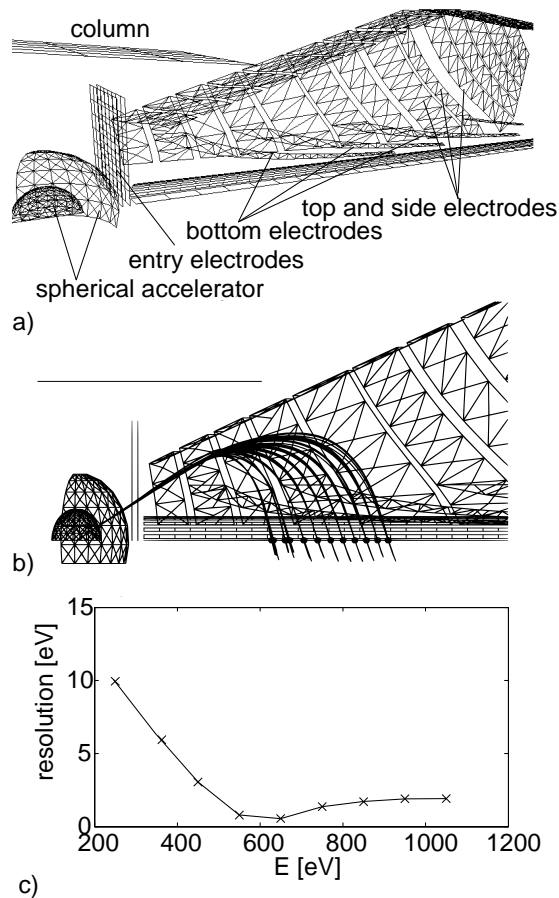


FIGURE 3. The 3D simulation with the CPO-3D software. a) Subdivided electrodes and description of the electrodes, b) Side view at electrodes and simulated trajectories. The sample is positioned in the center of the hemispherical accelerator. c) Dependence of the analyzer resolution on kinetic energy of analyzed electrons at the sample.

of the University of York, UK. In the past a hyperbolic field analyzer was used in this system and the new cylindrically symmetrical field system was designed to work in the same position in the microscope. Therefore, the new analyzer had to have similar shape. The shapes of the electrodes were then calculated according to this requirement.

PEEK and Kapton materials were used for the insulating parts of the device. Both materials are very stable at high temperatures and ultra-high-vacuum compatible. The PEEK was used to make insulating spacers. The top cover was made of Kapton. The electrodes were accurately etched of stainless steel sheet. The side covers and lower cylindrical electrode were made of an aluminium alloy.

A set of two concentric hemispheres was used as the accelerator, which produces the radial electrostatic

field, accelerates the electrons emitted from the sample, and decelerates primary electrons before they land on the sample. The point where the primary beam hits the specimen has to be in the center of the hemispheres. As an inlet and outlet for electrons, two round holes need to be drilled in the hemispheres. These affect the electron trajectories because they form a lens, but the negative effect on the trajectories entering the analyzer is significant only at the lowest energies. At higher energies this effect is negligible.

The analyzer was developed and built in the Institute of Scientific Instruments, Academy of Sciences of the Czech Republic.

EXPERIMENT

The analyzer was used to verify the previous ideas and calculations and to demonstrate that the cylindrically symmetrical field can be successfully used in parallel energy analysis. The analyzer was inserted into an ultra high vacuum system equipped with an electrostatic column. The pressure in the sample chamber was on the order of 10^{-8} Pa. As a sample a piece of copper foil was used, although the sample was not cleaned. For a detector the electrons were multiplied by micro channel plate and then converted to light quanta with a phosphor screen. The image on the screen was then photographed through a vacuum window using Konica-Minolta Z3 digital camera.

CONCLUSION

From the simulation, the absolute dispersion is nearly constant at $1.97 \times 10^{-2} \text{ mm} \cdot \text{eV}^{-1}$. The resolution varies from 10 eV to 2 eV, for most energies keeps below 2 eV, which well corresponds to [4]. The result of the experiment is a 400 pixel long spectrum. (See Fig. 4.) The relaxation peak is 1 pixel wide, which shows that the energy resolution is better than 3 eV (Fig. 4d) at 1500 eV, which satisfies the theoretical estimations. The experiment also showed the cylindrical focusing. In the photograph of the screen (Fig. 4b) different widths of illuminated area can be seen. These may be caused by a slight misalignment that occurred during bake-out. This fact also affects the signal levels of different channels. The peak between 300 eV and 500 eV is partially caused by carbon (the main matter covering the surface of the sample) because the sample was not cleaned.

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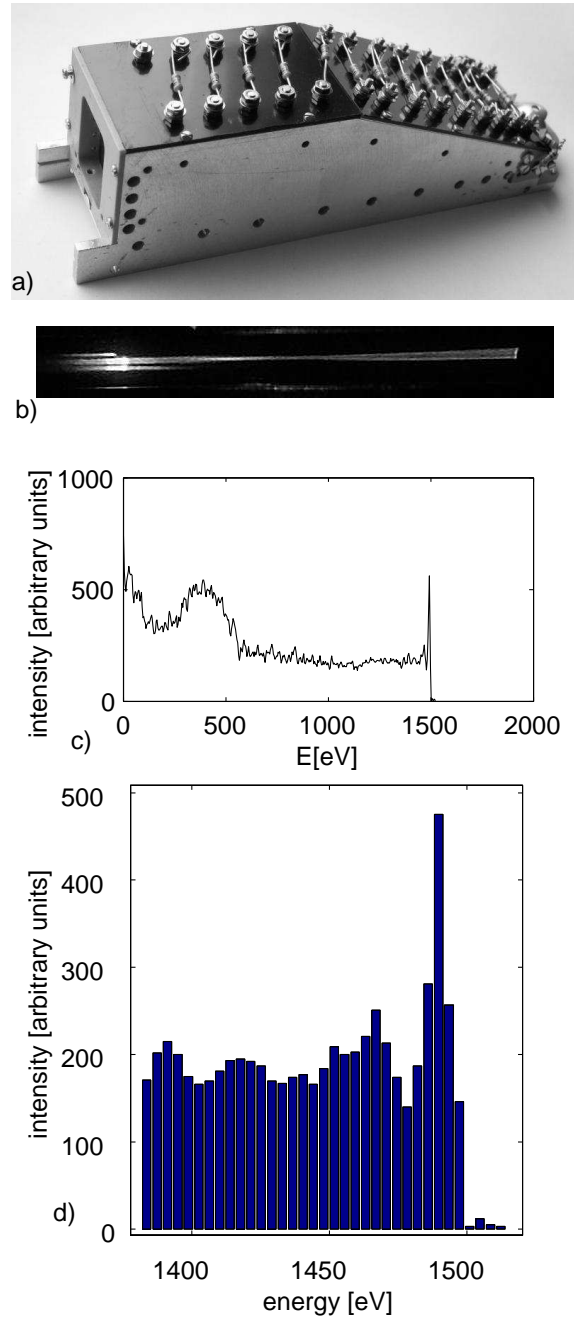


FIGURE 4. a) Photograph of the analyzer. b) Photograph of the phosphor screen when acquiring an uncorrected electron energy spectrum emitted from the contaminated copper sample taken at primary beam energy of 2500 eV. c) A sum of three acquisitions of the same spectrum. d) Detail of the relaxation peak displayed as a bar graph.